The 6300 Å Predawn enhancement: excitation by photoelectrons from the Magnetic conjugate point

by Vincent B. Wickwar,
Department of Geology and Geophysics, Yale University,
New Haven, Connecticut 06520.

Résumé. — On a combiné, à l’Observatoire d’Arecibo, des mesures par diffusion incohérente et par photométrie à filtre interférentiel oscillant, pour préciser la contribution au renforcement pré-épisculaire de la raie 6300 Å, de l’excitation par impact des photoélectrons issus du point magnétiquement conjugué.

Avant environ 105° d’angle zénithal solaire conjugué, les intensités 6300 Å observées sont en bon accord avec les intensités provenant de la recombinaison dissociative. A l’arrivée des photoélectrons conjugués (confirmée par le renforcement de la raie de plasma), les intensités observées s’élèvent au-dessus du niveau calculé dans l’hypothèse de la recombinaison dissociative et la différence augmente jusqu’à atteindre un plateau pour un angle zénithal solaire conjugué de 95° environ. L’intensité résiduelle est attribuée à l’effet d’excitation dû à l’impact direct des photoélectrons. Il y a des variations significatives, d’un jour à l’autre, de l’heure de début du phénomène et de l’intensité; elles sont fortement anticorrelated à la densité électronique ionosphérique.

Abstract. — Incoherent scatter and tilting filter photometer data from Arecibo Observatory were combined to search for a contribution to the 6300 Å predawn enhancement due to impact excitation by photoelectrons from the magnetic conjugate point. Prior to about 105° conjugate solar zenith angle, calculations of the 6300 Å intensities due to dissociative recombinaison gave good agreement with the observed intensities. Then, with the arrival of conjugate photoelectrons (confirmed by plasma line enhancements), the observed intensities rose above the calculated, the difference increasing until a plateau was achieved at a conjugate solar zenith angle of about 95°. The difference or residual intensity is attributed to direct photoelectron impact excitation. Significant day-to-day variations in the onset angle and intensity have a strong negative correlation with ionospheric electron density.

I. INTRODUCTION

The 6300 Å predawn enhancement refers to an increase in the emission from O$(^3P)$ during the winter which begins at approximately the time of sunrise in the ionosphere at the magnetic conjugate point. Barbier [1959] identified the phenomenon and Cole [1965] associated the onset with conjugate sunrise. There have been numerous studies of the phenomenon [BARBIER, 1959, 1961; CARLSON and WEILL, 1967; OKUDA and MISAWA, 1969; SMITH, 1969; INGHAM, 1969; NOXON and JOHANSON, 1970; NICHOL, 1970; SCHAEFFER, 1971], yet questions still remain concerning the excitation mechanism or mechanisms and the relationship to other solar-terrestrial phenomena.

Cole [1965] proposed that the flux of photoelectrons [HANSON, 1963] from the sunlit end of the magnetic field line would heat the ambient electrons at the dark end sufficiently that they could excite the atomic oxygen. Predawn electron temperature measurements by Carlson [1966] showed that the increase, while great, was not sufficient, and he instead proposed electron impact excitation directly by the conjugate photoelectrons.

The studies by Carlson and Weill [1967] and Okuda and Misawa [1969a] supported this interpretation while that by Noxon and Johanson [1970] was less definite and raised the possibility of an increase in the rate of dissociative recombination as an alternative source of the enhancement, i.e. an increase in the source of at least the low and middle latitude 6300 Å night-time airglow [PETERSON and VAN ZANDT, 1969; NOXON and JOHANSON, 1970; WICKWAR, COGGER and CARLSON, 1972]. The study by Schaeffer [1971] tended to support this latter possibility and Carlson and Walker [1972] have proposed a mechanism which could increase or decrease dissociative recombination during the predawn period, depending primarily upon the conjugate point location. In any case, one of the difficulties in examining the predawn enhancement has been its separation from the background dissociative recombination [NOXON and JOHANSON, 1970; WICKWAR and CARLSON, 1972]. In this connection Carlson [1972] discusses several F-region phenomena which would affect the background intensity and could therefore on occasion and/or at some locations interfere with interpretation of the enhancement.

This study determines and examines the photoelectron contribution to the enhancement by carefully calculating and subtracting the dissociative recombination contribution from the observed intensity. The procedure for calculation of the dissociative recombination contribution is given in section II. By continuing the night-time calculations into the predawn period, in section III, a photoelectron impact component is shown to exist. In section IV it is shown that common features are a growth period leading to a relatively constant plateau. However there is considerable variability in onset angle, 107° to 100° conjugate solar zenith angles, and plateau intensity, 20 to 55R, which can most likely be related to the electron density in the local ionosphere, rather than to parameters for solar or geomagnetic activity.

The data were gathered at Arecibo Observatory (L = 1.5, 18.35°N, 66.75°W) between October 1969 and March 1970. The conjugate point (46°49′S, 64.55°W) was found using the IGRF (10/68) coefficients [CAIN et al., 1968] updated to January 1970 by tracing the magnetic field line from 300 km above sea level at Arecibo to 300 km above sea level at the conjugate point.

II. THE DISSOCIATIVE RECOMBINATION CALCULATION

For excitation of O$(^3P)$ by dissociative recombination of O$_2$ [DALGARNO and WALKER, 1964; WALLACE and MCELROY, 1966], and quenching by N$_2$ [HUNTEN and MCELROY, 1966; WALLACE and MCELROY, 1966; NOXON, 1970], the intensity at 6300 Å in Rayleighs is given by [NAGATA and OGAWA, 1964; PETERSON et al., 1966; PETERSON and VAN ZANDT, 1969; WICKWAR et al., 1972]

\[
I(6300) = 0.076 \int \left( \frac{R_1 N_{O_2}(h)}{1 + Q N_{N_2}(h)/A} \right) dh
\]

\[
N_x(h) \left( \frac{1 + \gamma_1 N_{O_2}(h) + \gamma_2 N_{N_2}(h)}{\alpha_1 N_x(h) + \alpha_2 N_x(h)} \right)
\]

where the integration is over the region from which emission occurs, 200 km or below to about the peak of the F-layer. The equations governing the excitation and emission are given in Table I along with the coefficients \(\gamma_1, R, Q, \alpha_1, \alpha_2, \) and \(\gamma_2\), and the values used for the results presented here. Of these coefficients, the first three are the most important. The Einstein coefficients \(A_{6300}\) and \(A_{6364}\) [cf. CHAMBERLAIN, 1961] are summed to give \(A\) in sec$^{-1}$. The quantities \(N_x(h)\) give the number density of constituent \(x\) in cm$^{-3}$ at altitude \(h\) in km.

To use the integral, the electron density profiles, O$_2$ and N$_2$ profiles, and values of the Table I coefficients have to be known or determined. The electron density profiles can be obtained from ionograms [as in NOXON and JOHANSON, 1970] or from incoherent backscatter measurements [as in PETERSON and VAN ZANDT, 1969; WICKWAR et al., 1972]. In this case the profiles were obtained with the incoherent backscatter at Arecibo [GORDON and LALONDE, 1961, for description; CARLSON et al., 1970, for the experimental uncertainties]. The neutral densities can be obtained using temperature profiles from neutral atmosphere models and adjusting the base densities.
### Table I

Reactions and coefficients for the dissociative recombination calculation of the 6300 Å intensity.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Symbol</th>
<th>Definition</th>
<th>Value Used</th>
<th>Reference for a laboratory determined value *</th>
</tr>
</thead>
<tbody>
<tr>
<td>O⁺ + O₂ → O²⁺ + O</td>
<td>γ₁</td>
<td>reaction rate</td>
<td>2.0 × 10⁻¹¹ cm³/sec</td>
<td>Smith and Fouracre [1968]</td>
</tr>
<tr>
<td>O²⁺ + e → O + O</td>
<td>γ₂</td>
<td>reaction rate</td>
<td>1.95 × 10⁻⁷ (300 / Tₐ)² cm³/sec</td>
<td>Dunkin et al. [1968]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>number of O(D)'s per recombination</td>
<td>0.5</td>
<td>Mehr and Biondi [1969]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>quenching coefficient</td>
<td>5.5 × 10⁻¹¹ cm³/sec</td>
<td>Zipf [1970]</td>
</tr>
<tr>
<td>N₂ + O(D) → N₂ + O(ÇP)</td>
<td>Q</td>
<td>reaction rate</td>
<td>2.0 × 10⁻¹⁸ cm³/sec</td>
<td>Noxon [1970]</td>
</tr>
<tr>
<td>O⁺ + N₂ → NO⁺ + N</td>
<td>γ₁</td>
<td>reaction rate</td>
<td>4.1 × 10⁻⁷ (300 / Tₐ)³ cm³/sec</td>
<td>Fite [1969]</td>
</tr>
<tr>
<td>NO⁺ + e → N + O</td>
<td>γ₂</td>
<td>reaction rate</td>
<td></td>
<td>Biondi [1969]</td>
</tr>
</tbody>
</table>

*The references contain recent discussions, but not necessarily the values used.*

i.e. the densities at 120 km in most models. Comparable results were obtained using both the CIRA 1965 [CIRA, 1965] and Jacchia, 1965 [JACCHIA, 1965] temperature profiles [WICKWAR et al., 1972], with the time evolution of the parameter $T_0$ given by CIRA, 1965. The only significant difference encountered was in the value of $T_0$ needed to define the time evolution curve. The base densities used were adapted from von Zahn [1970] for 120 km: 3.9 × 10¹⁰ cm⁻³ for O₂ and 3.1 × 10¹¹ cm⁻³ for N₂. Procedures for adjusting the Table I coefficients and base densities by comparing observed and calculated intensities [PETERSON and STEIGER, 1966; PETERSON and VAN ZANDT, 1969; NOXON and JOHANSON, 1970; WICKWAR et al., 1972] were used for four winter nights when the conjugate solar zenith angle, $\chi_C$, was greater than 110° to obtain the values already given such that only $T_0$ had to be varied thereafter to fit any given night. It should, however, be stressed that there is a whole family of coefficients and base densities which will fit these Arecibo observations even though they were made under a wide variety of F-region conditions, and that under some geophysical circumstances even this family of coefficients and densities might change [WICKWAR et al., 1972]. Hence, although the coefficients are similar to laboratory determinations or their extrapolations [cf. references in Table I] and the base densities are related to rocket measurements [cf. VON ZAHN, 1970], the good agreement achieved between observation and calculation does not of itself confirm that each value is correct, only that the set of values is consistent [WICKWAR et al., 1972].

**III. ELECTRON IMPACT EXCITATION**

Figure 1 compares photometer observations obtained with a tilting filter photometer [EATHER and REASONER, 1969] for 13-14 November 1969, with three dissociative recombination calculations. The photometric data have an accuracy of about 15% and a precision of about 3%. Since the calculations differ from one another by 50° in the parameter $T_0$ at 0200, it follows that $T_0$ can be chosen with a precision greater than 50° before about 0230, with a resultant precision of about 6R in matching the observed and calculated intensities. After about 0245 the curves separate, with the observed intensity
greater than the calculated. There is no way in which the difference can be removed by adjusting the model atmosphere or the rate coefficients while maintaining the good fit obtained earlier in the night.

Figure 1 further shows that 0245 corresponds to about $\chi_e = 105^\circ$ which is approximately the angle for sunrise in the conjugate ionosphere, and hence the angle at which conjugate photoelectrons should first appear. In fact, this is approximately the angle at which the arrival of conjugate photoelectrons is directly confirmed by the onset of plasma line detection in the incoherent backscatter signal [WICKWAR and CARLSON, 1972 a and b]. A photoelectron flux both excites plasma waves and modifies the Landau damping of these waves such that otherwise undetectable plasma line backscatter signals become detectable [PERKINS and SALFETER, 1965; YNGVESSON and PERKINS, 1968]. Therefore plasma line observations offer a direct means of determining the presence of photoelectrons. Thus the difference between the curves in figure 1 is attributed to the arrival of conjugate photoelectrons. Furthermore, the ambient electrons remain at low enough temperatures that they cannot cause more than about 1R of enhancement [CARLSON, 1966; DUBOIX et al., 1968; WICKWAR and CARLSON, 1972 a]. Therefore the excitation must arise from direct impact by the incident conjugate photoelectrons.

IV. Variability of the Impact Component and the Local Ionosphere

Figure 2 shows the photoelectron induced predawn enhancement for three of seven days examined during the winter of 1969-1970, all of which had coincident photometer and backscatter data. These three days indicate the range of variability observed, but otherwise resemble the other days in that the enhancement has a period of rapid growth followed by a plateau period of nearly constant intensity until local sunrise effects begin. The onset of the growth period is shown ranging from about 10° to 10° conjugate solar zenith angle, with the plateau beginning between 95° and 90° and having an intensity of 20 to 55R. However, as shown by curves b and c, an earlier onset does not necessarily lead to a greater plateau intensity. The matching between observed and calculated intensity before conjugate sunrise, e.g. Figures 1 and 2 for $\chi_e > 105^\circ$, is good enough that the variation in onset angle, rate of intensity increase and plateau intensity are significant.

Day-to-day variations in the onset angle and plateau intensity do not correlate well with the small variations that occurred in solar or geomagnetic activity, i.e. with $S_p$, or $K_p$, nor did these parameters vary rapidly enough to account for the different rates of intensity increase. However, as shown in Table II, the critical frequency and electron content of the

![Graph](image)

**Figure 2**

Three examples of the 6300 Å photoelectron impact component which indicate the range of variability in onset angle and intensity encountered during the 1969/1970 winter at Arecibo. On 2/3 February, there is no backscatter date between 109° and 103°. For comparison with the observed intensity and the dissociative recombination intensity, see Figure 1 of Carlson [1972].

**Table II**

<table>
<thead>
<tr>
<th>Date</th>
<th>Onset</th>
<th>Plateau Intensity for $\chi_e = 85^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\chi_e$</td>
<td>$f_{0}F_{2}$</td>
</tr>
<tr>
<td>----------------</td>
<td>----------</td>
<td>-------------</td>
</tr>
<tr>
<td>14 Nov. 1969</td>
<td>107°</td>
<td>4.6 MHz</td>
</tr>
<tr>
<td>23 Jan. 1970...</td>
<td>100°</td>
<td>6.6 MHz</td>
</tr>
<tr>
<td>3 Feb. 1970....</td>
<td>&gt; 103°</td>
<td>4.9 MHz</td>
</tr>
<tr>
<td></td>
<td>&lt; 109°</td>
<td>4.9 MHz</td>
</tr>
</tbody>
</table>
local ionosphere do vary significantly from day-to-day during the predawn period. Also their amount and rate of variation during the predawn period varies considerably from day-to-day. Additionally, they have a strong negative correlation with the onset angle and plateau intensity. Thus a model is obtained in which the conjugate flux emerging from the magnetic field tube was to first order constant for these observations and was then modulated by the local ambient electron density. Provided such modulation could account for the variation in plateau intensity, it would also account for the different rates of intensity increase and variation in onset angle. For example, for greater local density near the onset angle, the reduced conjugate flux would remain below the amount needed to produce a detectable 6300 Å intensity until the incident conjugate flux had itself increased enough with decreasing $\chi_e$ to overcome the additional loss. This model will be discussed at greater length in Wickwar and Carlson [1972 a].

V. CONCLUSION

By performing a detailed calculation of the 6300 Å intensity resulting from dissociative recombination and subtracting it from the total observed intensity, it becomes possible to determine the contribution due to impact by conjugate photoelectrons. At Arecibo in the northern winter of 1969-1970 an impact component of 20 to 55R has been found. The average photoelectron contribution is about half of the total intensity [Wickwar and Carlson, 1972 a].

The development of the impact component as a function of conjugate solar zenith angle has the same basic shape for the days observed, but there is considerable variability in the onset angle, rate of intensity increase, and plateau intensity. The variability is strongly related to the local electron density, implying that the local ionosphere, as predicted by Noxon and Johansen [1970], is an important region for modulating the conjugate photoelectron flux. No strong correlation appears with solar or geomagnetic parameters.

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